

SHOCK EXCITED MOLECULES IN NGC 1266: ULIRG CONDITIONS AT THE CENTER OF A BULGE-DOMINATED GALAXY

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ABSTRACT

We investigate the far infrared (IR) spectrum of NGC 1266, a S0 galaxy that contains a massive reservoir of highly excited molecular gas. Using the *Herschel* Fourier Transform Spectrometer, we detect the ¹²CO ladder up to $J = (13-12)$, [C I] and [N II] lines, and also strong water lines more characteristic of UltraLuminous IR Galaxies (ULIRGs). The ¹²CO line emission is modeled with a combination of a low-velocity C-shock and a photodissociation region. Shocks are required to produce the H₂O and most of the high- J CO emission. Despite having an IR luminosity 30 times less than a typical ULIRG, the spectral characteristics and physical conditions of the interstellar medium of NGC 1266 closely resemble those of ULIRGs, which often harbor strong shocks and large-scale outflows.

Key words: galaxies: individual (NGC 1266) – infrared: ISM – ISM: jets and outflows – ISM: lines and bands – ISM: molecules – photon-dominated region (PDR)

Online-only material: color figures

1. INTRODUCTION

The IR emission of galaxies beyond the peak of their thermal dust emission, from 200–600 μ m, traces their ionized, neutral, and molecular interstellar medium (ISM). In particular the ¹²CO transitions (hereafter CO) from $J = 4-3$ to $J = 13-12$ provide an important diagnostic of molecular gas excitation. These CO spectral line energy distributions (SLEDs) allow one to distinguish those regions within galaxies dominated by star formation (SF; photodissociation regions (PDRs, also referred to as photon-dominated regions)) or by active galactic nucleus (AGN) produced X-ray dominated regions (XDRs).

At a distance of 29.9 Mpc ($z = 0.0073$), NGC 1266 contains $1.1 \times 10^9 M_{\odot}$ of molecular gas within a 100 pc radius, with a denser, 60 pc core containing $4 \times 10^8 M_{\odot}$ of gas (Alatalo et al. 2011). In contrast, nearby giant molecular clouds of a similar size contain only $10^6 M_{\odot}$ of gas

(Fukui & Kawamura 2010). The core mass and projected size corresponds to a surface density of $2.7 \times 10^4 M_{\odot} \text{ pc}^{-2}$, similar to what is observed in UltraLuminous IR Galaxies (ULIRGs; Bothwell et al. 2010). Its *IRAS* 60/100 μ m ratio is twice as large as the median value of more ordinary galaxies within the SINGS sample (Dale et al. 2009), yet within 5% of the mean ratio of 41 ULIRGs (Farrah et al. 2003). The observed 9.7 μ m silicate optical depth $\tau(\text{Si}) \approx 2$ (*Spitzer*-Infrared Spectrograph spectra; Smith et al. 2007). The ISM column density and dust colors are quite comparable with samples of ULIRGs, despite NGC 1266's total infrared luminosity (TIR) of only $2.75 \times 10^{10} L_{\odot}$.

Broad velocity wings of the low- J CO lines reveal a massive and energetic molecular outflow ($\dot{M}_{\text{out}} = 2.4 \times 10^7 M_{\odot} \text{ yr}^{-1}$; Alatalo et al. 2011). The mass outflow rate exceeds the SF rate by a factor of five, leading to a highly obscured, weak AGN as a likely driving mechanism (Alatalo et al. 2011).

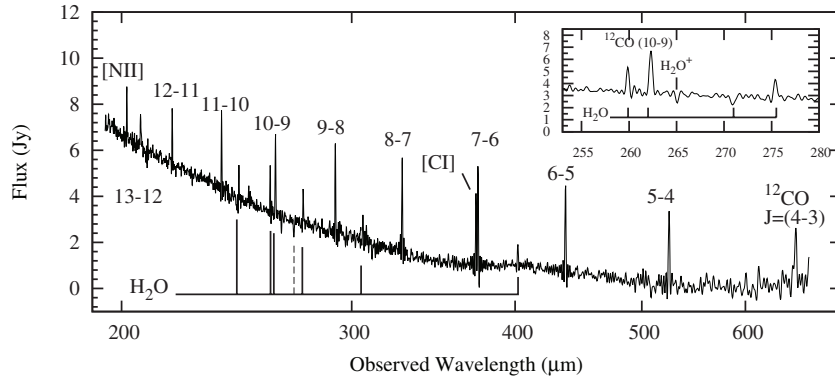


Figure 1. SPIRE-FTS spectrum from 200 to 600 μm . Emission lines include ^{12}CO from $J = (4-3)$ to $J = (13-12)$, [N II] 205, [C I] 370 and 609 μm . Strong ortho and para H_2O emission characteristic of ULIRGS is seen in emission (solid line) as well as absorption (dashed line).

Evidence of mechanical feedback is also detected in optical lines from ionized gas, with shock velocities $\approx 500 \text{ km s}^{-1}$ (Davis et al. 2012).

2. OBSERVATIONS

Our observations include *Herschel* Fourier Transform Spectrometer (SPIRE-FTS) spectroscopy obtained as part of the “Beyond The Peak” (BTP; OT1_jsmith1; PI: J. D. Smith) survey of 21 nuclear regions and 2 extra-nuclear regions selected from the SINGS (Kennicutt et al. 2003) and KINGFISH (Kennicutt et al. 2011) surveys. BTP provides deep, intermediate spaced mapping of a large collection of nearby galaxies at ^{12}CO transitions above $J = (3-2)$.

2.1. PACS Spectroscopy

NGC 1266 has been imaged in [C II], [O I], [O III], and [N II] emission lines as part the *Herschel* key program KINGFISH (Kennicutt et al. 2011). The data were using the KINGFISH pipeline for PACS spectroscopy in HIPE v9.0.3063 using the calibration files in PACS calVersion 41, following the methods described in Croxall et al. (2012).

2.2. SPIRE-FTS Spectroscopy

All SPIRE-FTS observations use a four-point dither which sub-critically samples extended emission with an internal jiggle mirror. Our data are calibrated with HIPE v10 using an extended-flux calibration. The default pipeline includes a central,unjiggled telescope response function (RSRF) created from thousands of repetitions of dark observations. We calculate new jiggled RSRFs from $\simeq 100$ repetitions of jiggled darks, now available in HIPE v11. For dark subtraction, we use the unjiggled deep darks obtained during the same FTS observing run and fit a high-order polynomial to each bolometer.

While NGC 1266 is a compact source, the Long Wavelength Spectrometer (SLW) bolometer beam size and dither pattern produce repeat, but off-center SLW observations of our target. At this time, dithered calibrations have only been obtained for extended sources. To calibrate these dithered observations we begin with the Jiggle-0 (undithered) spectrum, processed with the point-source pipeline. Next all data were re-processed as with mapped calibrations, and an average spectrum was created by weighting individual SLW bolometers with the projected overlap of the beam profile and a $20''$ aperture centered on the peak of the SPIRE 250 μm image (Kennicutt et al. 2011). We ratio the mapped and point-source spectra to create a

transfer function to calibrate the dithered observations while simultaneously accounting for the beam filling factor of a point source. Off target bolometers also sample ample sky around NGC 1266 and we find no continuum or line emission, and thus perform no background subtraction.

The resulting spectrum (Figure 1) shows prominent lines of [N II], [C I], 10 transitions of ^{12}CO , and 7 transitions of H_2O . We measure emission line fluxes from the unapodized spectrum using sinc profiles with a variable spectral width. Due to outflows we allow line central velocities to vary up to 100 km s^{-1} from the systematic velocity. The line fluxes and errors associated with the continuum uncertainty are listed in Table 1, which also includes ground based measurements of ^{12}CO $J = (1-0)$, $(2-1)$, and $(3-2)$ from Alatalo et al. (2011). In addition to the H_2 lines from *Spitzer* IRS, we also add NIR 1–0 S(1) H_2 fluxes from Riffel et al. (2013).

The Table 1 line fluxes are extinction-corrected using the PAHFIT fully mixed geometry decomposition of NGC 1266’s low resolution IRS spectroscopy, which yielded a silicate opacity $\tau_{9.7\mu\text{m}} = 2.05$. The correction if we adopt a screen geometry is negligibly different.

3. POWERING MOLECULAR EMISSION

We consider energy sources that are capable of powering the emission from the central 100 pc of NGC 1266: an AGN and SF. X-ray emission from an obscured AGN could produce an XDR, while SF would produce a PDR. Both phenomena are also capable of driving shocks, which would mechanically heat the gas. However, we emphasize that the dominance of one heating mechanism does not preclude the presence of the other.

3.1. CO and H_2

3.1.1. Shocks

Motivated by shocks detected in optical lines, and molecular outflows, we first consider shocked gas as the source of CO excitation. To fit the CO SLED, we form combinations of the J- and/or C-shock models from Flower & Pineau Des Forêts (2010). We then fit these to observations after normalization by total intensity from $J = (1-0)$ to $(13-12)$ according to

$$I_{\text{norm}}(J_i) = \sum_k f_k(^{12}\text{CO}) \times \frac{I_k(J_i)}{\sum_{i=1}^{13} I_k(J_i)}, \quad (1)$$

where the k th model contributes a fraction f_k to the total predicted CO intensity, with a minimum $f_k = 0.01$ and $\sum_k f_k = 1$.

Table 1

NGC 1266 IRS, PACS, and SPIRE-FTS Extinction-corrected Line Fluxes

Species	Trans	Wave (μm)	Flux ($10^{-17} \text{ W m}^{-2}$)	Inst.
^{12}CO	1–0	2600	0.063 ± 0.004	1
^{12}CO	2–1	1300	0.39 ± 0.015	1
^{12}CO	3–2	867.0	1.02 ± 0.11	1
^{12}CO	4–3	650.7	2.69 ± 1.14	2
^{12}CO	5–4	520.6	3.84 ± 0.69	2
^{12}CO	6–5	433.9	4.28 ± 0.35	2
^{12}CO	7–6	371.9	4.76 ± 0.28	2
^{12}CO	8–7	325.5	4.71 ± 0.36	2
^{12}CO	9–8	289.3	4.64 ± 0.65	2
^{12}CO	10–9	260.4	3.94 ± 0.60	2
^{12}CO	11–10	236.8	4.03 ± 0.61	2
^{12}CO	12–11	217.1	2.85 ± 0.30	2
^{12}CO	13–12	200.4	2.65 ± 0.58	2
H_2O	2 ₁₁ –2 ₀₂	398.9	1.09 ± 0.32	2
H_2O	2 ₀₂ –1 ₁₁	303.7	2.91 ± 1.04	2
H_2O	3 ₁₂ –3 ₀₃	273.4	1.80 ± 0.40	2
H_2O	3 ₁₂ –2 ₂₁	260.2	1.83 ± 0.61	2
H_2O	3 ₂₁ –3 ₁₂	258.0	2.38 ± 0.45	2
H_2O	2 ₂₀ –2 ₁₁	244.1	1.69 ± 0.45	2
H_2O	4 ₂₂ –4 ₁₃	248.2	<0.47	2
H_2O	5 ₂₃ –5 ₁₄	212.5	<0.47	2
[C I]	...	370.7	3.19 ± 0.26	2
[C I]	...	609.6	1.13 ± 0.86	2
[C II]	...	157.7	17.30 ± 0.46	3
[O I]	...	63.18	11.40 ± 1.32	3
[N II]	...	205	1.70 ± 0.88	2
H_2	S(4)	8.026	21.90 ± 1.01	4
H_2	S(3)	9.662	13.00 ± 0.39	4
H_2	S(2)	12.282	10.90 ± 0.26	4
H_2	S(1)	17.035	8.48 ± 0.10	4
H_2	S(0)	28.171	2.94 ± 0.22	4
H_2	1–0 S(1)	2.1213	10.90 ± 0.20	5

Notes. Ground ^{12}CO from ¹Alatalo et al. (2011). Lines observed with ²SPIRE-FTS, ³PACS, ⁴Spitzer-IRS instruments. NIR H_2 from ⁵Riffel et al. (2013). IRS fluxes have been extracted over a $10''$ aperture centered on the peak of the IR continuum emission which is unresolved by *Spitzer* and *Herschel*.

With a large reservoir of dense gas we expect some level of SF in NGC 1266. The observed TIR emission is consistent with $\text{SF} \approx 2.1 M_\odot \text{ yr}^{-1}$ (Alatalo et al. 2011). So we consider combinations of shock and plane-parallel PDR models. To estimate the emission from PDRs, we adopt the models of Wolfire et al. (2010), with updates in Hollenbach et al. (2012). Note that we adopted the shock and PDR models with solar abundance as calculated. We do not include the 60/100 μm ratio from the dust spectral energy distribution as a constraint due to uncertainties in the optical depth of the dust emission. However, we do constrain $\beta_{\text{CO}} = L_{\text{CO}}/L_{\text{TIR}}$ not to exceed the observed ratio, based upon the assumption that shocks do not contribute appreciably to L_{TIR} and that a single face-on PDR contributes a continuum with an intensity related to the far-UV radiation field G_0 as

$$I_{\text{TIR}}(G_0) \simeq \frac{3 \times 1.6 \times 10^{-3}}{4\pi} \times G_0 (\text{erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}). \quad (2)$$

A PDR fits the lowest- J CO lines with $n(\text{H}) = 10^{3.5} \text{ cm}^{-3}$, $\log G_0 = 2.25$, while C-shocks fit the higher- J lines with $v = 30 \text{ km s}^{-1}$, $n(\text{H}) = 2 \times 10^4 \text{ cm}^{-3}$ (reduced $\chi^2 = 2.6$). The best-fitting combination of the existing models are shown

in Figure 2(a) with a solid line (black), as well as the individual PDR (blue) and shock (red) components. Model parameter probability distribution functions are shown on the right. The NGC 1266 H_2O SLED is also shown top-right. Although it was not used as an input, the best-fit model reproduces it well, including the faint high temperature transitions. The shock under-predicts the [O I] 63, but the [O I] intensity varies strongly with shock parameters. A small contribution from a 10 km s^{-1} shock we would explain the observed [O I] intensity.

3.1.2. PDR+PDR

A dual-PDR model ($n_1(\text{H}) = 10^{3.75} \text{ cm}^{-3}$, $G_{0,1} = 10^6$; $n_2(\text{H}) = 10^{5.5}$, $G_{0,2} = 10^{3.5}$) could equally well explain the ^{12}CO and H_2 excitation and relative intensity. We reject the dual-PDR scenario because it requires $G_0 \approx 10^4$ – 10^6 , resulting in β_{CO} 1000 \times lower than that observed. Meijerink et al. (2013) similarly rejected a dual PDR in NGC 6240 based on this argument. In NGC 1266, a dual PDR under-predicts β_{CO} , and hence over-predicts L_{TIR} , by three orders of magnitude. With β constrained to $\geq 4.6 \times 10^{-4}$, the resulting reduced χ^2 is ≥ 170 . Thus a two component PDRs is rejected as the sole source of the molecular emission.

3.1.3. XDR

The *ROSAT* X-ray flux of $2.49 \times 10^{-13} \pm 0.3 \text{ erg s}^{-1} \text{ cm}^{-2}$ from 0.2–2.0 keV (White et al. 1995) could also indicate an XDR contribution to ^{12}CO and the H_2O lines detected in our spectrum. We will fully explore the possible contribution of XDRs in our full survey, which includes 10 AGNs, in a future paper. However, an XDR is unlikely to dominate the ^{12}CO emission in NGC 1266. First, XDRs produce high ionization fractions in molecular gas leading to H_2O^+ and OH^+ emission with comparable intensities to H_2O lines (van der Werf et al. 2010; Meijerink et al. 2013), yet no emission from these molecules is detected. We do detect absorption from H_2O^+ , but this has been seen in systems where XDR are ruled out (e.g., Arp220; Rangwala et al. 2011).

Second, β_{CO} also eliminates XDRs as the dominant heating source in NGC 1266. The efficiency at which X-rays are converted to line emission and IR continuum is very different than in shocks which heat gas but are relatively inefficient at heating dust. This is illustrated in Figure 3, a plot of β_{CO} against $\beta_{[\text{C I}]}$ and $\beta_{\text{H}_2\text{O}}$. As discussed in Meijerink et al. (2013), XDR and PDR models have an upper limit on the line-to-continuum ratio of $\beta_{\text{CO}} \leq 10^{-4}$, represented by the dashed line in Figure 3. In NGC 1266 that ratio for the 13 detected CO lines is nearly 10^{-3} , just below that of NGC 6240 (see Figure 3). Alatalo et al. (2011) found that the observed β_{H_2} ratio was three times larger than could explained by an XDR. The ratio of $\beta_{[\text{C I}]}$ is also enhanced by an order of magnitude in NGC 1266, as in NGC 6240. The linearity of [C I] with ^{12}CO , seen in Figure 3, suggests it is a powerful diagnostic especially useful where the entire ^{12}CO is not observable, as is the case with high redshift galaxies observed with ALMA.

3.2. Shocked H_2O

The gas phase abundance of H_2O is driven by two processes: formation via endothermic reactions and the release from ices on the surface of dust grains. J- and C-shocks, as well as XDRs, are capable of producing the warm and dense molecular gas characteristic of H_2O emitting regions.

H_2O emission is not included in the Wolfire et al. (2010) PDR models because it is very faint. Therefore, we assume

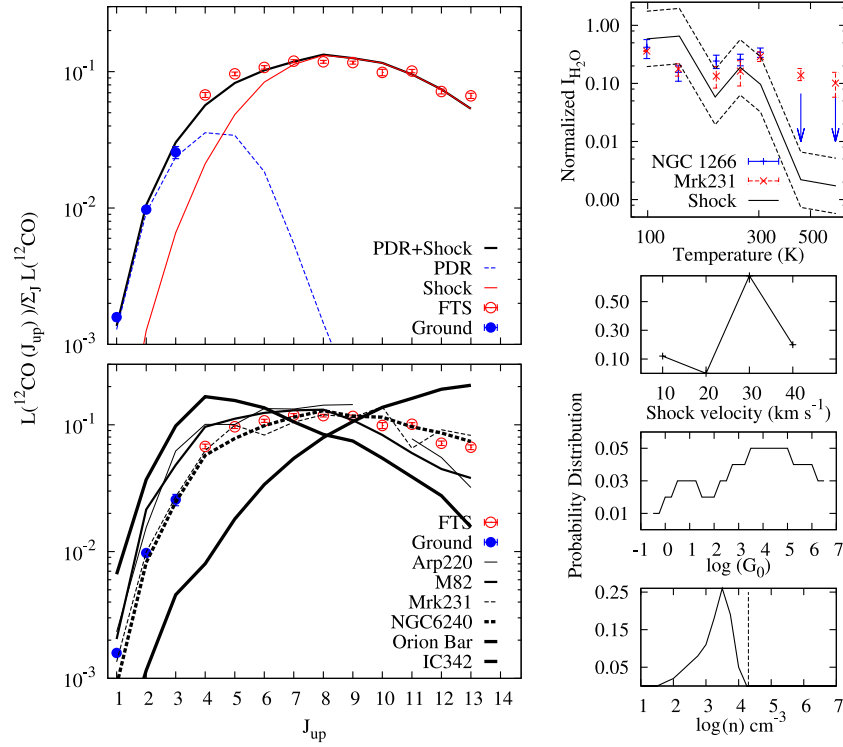


Figure 2. Top-left: NGC 1266 ^{12}CO SLED (up to $J = (13-12)$; circles) normalized by total observed ^{12}CO luminosity. Shown is the best-fitting PDR (dashed blue) and shock model (solid red). Bottom-left: comparison of ^{12}CO SLEDs of various galaxies, and the Orion Bar. Right: the H_2O SLED includes NGC 1266, Mrk231 and the best-fit shock model with a factor of three uncertainty in individual lines. Normalized probability distributions functions of the PDR+Shock parameters, and the H_2O SLED. A vertical dashed-line represents the only pre-shock density that fits observations. (A color version of this figure is available in the online journal.)

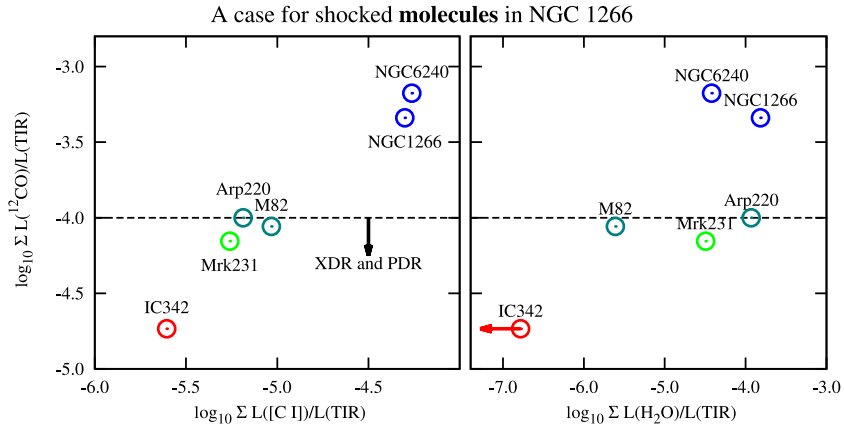


Figure 3. Left: total CO, from $J = (1-0)$ to $(13-12)$, relative to TIR, and $[\text{C I}]_{370.609 \mu\text{m}}$ relative to TIR for galaxies with detected H_2O emission and a detailed analysis of gas excitation mechanisms. Galaxies are color coded as PDRs (red), XDRs (green), mechanical (teal), and shocks (blue). Right: same as left, with total $L(\text{H}_2\text{O})/L(\text{TIR})$ on the x-axis. The horizontal dashed line marks the upper limit of $L(\text{CO})/L(\text{TIR})$ for XDRs and PDRs (Meijerink & Spaans 2005; Meijerink et al. 2007). (A color version of this figure is available in the online journal.)

the Orion Bar value of $L(\text{H}_2\text{O})/L(\text{CO}) = 0.001$ (Habart et al. 2010) for our modeled PDRs. The observed parameters of the Orion Bar PDR $G_0 \approx 4 \times 10^4$ (Tielens & Hollenbach 1985) and $n(\text{H}) \approx 10^5 \text{ cm}^{-3}$ (Allers et al. 2005; Pellegrini et al. 2009) are of higher density and excitation than the PDR parameters necessary to explain the low excitation CO in NGC 1266. These energetic conditions favor the formation of water, and thus provide an upper limit to the H_2O emission we expect from the PDR.

Table 2 and Figure 3 summarize the ratio of H_2O , ^{12}CO , and $[\text{C I}]$ to $L(\text{TIR})$. We examine the ratio of H_2O to ^{12}CO because both originate in molecular gas, unlike the IR continuum. The

Shock+PDR combination predicts a $L(\text{H}_2\text{O})/L(\text{CO}) = 0.34$, very similar to the NGC 1266 value of 0.33. The observed value is also similar to that found in the XDR heated Mrk231 (van der Werf et al. 2010), and the mechanically heated Arp220 (Rangwala et al. 2011). Thus, total $L(\text{H}_2\text{O})$ relative to $L(\text{CO})$ or $L(\text{TIR})$ is limited as a shock diagnostic because it can be enhanced by radiative pumping in systems with high gas column densities, resulting in bright emission from high levels of H_2O . However, in a sample of IR pumped galaxies, typical H_2O transitions are $\text{H}_2\text{O } 2_{02}-1_{11}/4_{22}-4_{13} \leq 2.5$ (Yang et al. 2013). In Figure 2 $\text{H}_2\text{O } 4_{22}-4_{13}$ and $5_{23}-5_{14}$ are undetected in NGC 1266, with $2_{02}-1_{11}/4_{22}-4_{13} \geq 4.0$. Thus, the intense emission and

Table 2
Line to Continuum Ratios

Object	$L(\text{TIR})$ $\times 10^{10}$	$L(\text{CO})/L(\text{TIR})$ $\times 10^{-5}$	$L(\text{H}_2\text{O})/L(\text{TIR})$ $\times 10^{-7}$	$L([\text{C I}])/L(\text{TIR})$ $\times 10^{-6}$	Heating
IC342 ^a	1.3	1.77	1.59	2.5	PDR
M82 ^b	5.6	8.75	24.5	9.3	Mech
NGC 6240 ^c	75	66.7	380	54.7	Shock
NGC 1266 ^d	2.4	45.8	1534	50.0	Shock
Mrk231 ^e	400	7.00	321	5.5	XDR
Arp220 ^f	200	10.0	1170	6.5	Mech

Notes. ^a Rigopoulou et al. 2013; ^b Kamenetzky et al. 2012; ^c Meijerink et al. 2013; ^d this work; ^e van der Werf et al. 2010; ^f Rangwala et al. 2011.

weak excitation of H₂O emission provides strong evidence for shock heating of molecular gas in NGC 1266.

4. DISCUSSION

4.1. Driving Shocks: Star-formation or an AGN

The shock model which fits the CO SLED converts 70% of incident mechanical power into observable H₂ emission. Taking the observed $L(\text{H}_2) = 1.5 \times 10^7 L_\odot$, this requires a incident mechanical luminosity of $2.1 \times 10^7 L_\odot$.

Alatalo et al. (2011) argued for an AGN based on the ratio of mass outflow to SF rate of $\dot{M}_{\text{out}}/\dot{M}_{\text{SF}} = 5$. However, recent models used to explain massive outflows in high redshift galaxies find SF driven outflow rates between 1–8×SF rate (Bournaud et al. 2013), suggesting SF could dominate. To determine the possible contribution from SF we assume the core SF rate is $2.1 M_\odot \text{ yr}^{-1}$ (Alatalo et al. 2011). From Hopkins et al. (2011), the energy injection rate into a turbulent medium is

$$\dot{E} = (1 + \eta_p \tau) \times 4 \times 10^{-4} \times \text{SF} \times c \delta v. \quad (3)$$

We assume radiation and winds contribute equally to the momentum injection rate ($\eta_p = 2$), neglecting supernovae. τ is the optical depth of IR radiation, weighted by the momentum of each photon, which we conservatively take to be unity. δv is the width of the gas velocity distribution. Adopting the core CO line widths of 100 km s^{-1} , we find $\dot{E}(\text{SF}) = 1.3 \times 10^7 L_\odot$. Thus, given uncertainties in τ and η_p , a SF of $2.1 M_\odot \text{ yr}^{-1}$ could sustain the energetics of the derived shocks indefinitely.

The mechanical energy injected by jets from the central radio source has also been estimated assuming the central source is an AGN (K. Nyland et al., in preparation). The implied jet power is $2.5\text{--}14 \times 10^8 L_\odot$, more than sufficient to power the shocks. Thus we find SF, an AGN, or the combination of the two, can drive the observed shocks.

4.2. Dual PDRs

A dual PDR is not able to simultaneously match the ¹²CO SLED and TIR. Relaxing the constraint of β_{CO} , the CO SLED can also be fit with two PDRs, representing the high density core and envelope at 100 pc, with a reduced $\chi^2 = 3.3$. This highlights that the CO SLED of NGC 1266 alone cannot unambiguously distinguish PDRs from shocks.

H₂ emission also fails to distinguish a dual PDR from a PDR+Shock, with the total H₂ intensity relative to CO roughly twice that observed in both models. Similarly, the individual H₂ line ratios relative to total observed CO are similar and do not break the degeneracy between linear combinations of PDRs or shocks and PDRs.

4.3. ULIRG Physical Conditions

The high IR-surface-brightness and gas densities found within the core of NGC 1266 are closely analogous to the physical conditions of many ULIRGs.

Like many ULIRGs, NGC 1266 possesses an outflow in ionized and molecular gas. In ULIRGs with outflows H₂O absorption lines are blueshifted by 100s km s^{-1} relative to those in emission (i.e., Mrk231; van der Werf et al. 2010). Our data show broad [C II] emission ($\sigma_v = 264 \text{ km s}^{-1}$), but H₂O and CO line centers are within 40 km s^{-1} of each other, implying a stronger connection between H₂O and ¹²CO in NGC 1266 than in ULIRGs.

The lower than average ¹³CO/¹²CO in NGC 1266 is also a characteristic of LIRGs and ULIRGs (Aalto et al. 1995), and indicates a low CO optical depth generally attributed to a highly turbulent medium. We speculate that in NGC 1266, a similar molecular gas velocity structure is the result of shocks. Unlike some ULIRGs, this shocked material is unlikely the result of a merger, as no extended H I emission has been detected (Alatalo et al. 2011). A high density is corroborated by molecular line ratios, such as HCN/¹³CO which is an order of magnitude larger than those observed in other early-type galaxies (Crocker et al. 2012), and also similar to ULIRGs.

The infrared energy distribution observed with *Spitzer* and *Herschel* indicates the dust in NGC 1266 is heated by a radiation field with $G_0 = 20$. Assuming a spherical distribution of gas and dust with $N(\text{H})/A_V = 5.3 \times 10^{-22} \text{ mag cm}^2$, a radius of 60 pc, and $\tau(\text{Si})/A_V = 20$ (Chiar & Tielens 2006), we find $A_V \sim 10^3 \text{ mag}$, $A_{8\mu\text{m}} = 38$, and $\tau(\text{Si}) \approx 50$ to the center of NGC 1266. This is much larger than observed, and whichever physical process energizes the IR continuum, the observed ($\approx 10 \text{ s } \mu\text{m}$) continuum emission cannot originate at the center of NGC 1266 behind the highest possible column.

5. CONCLUSIONS

The dominant energetic source of gas excitation within NGC 1266 is challenging to determine. The extreme column densities of dust are capable of hiding otherwise unambiguous diagnostics of AGN or SF. SPIRE-FTS observations of mid-*J* CO and H₂O emission now provide the strongest evidence to date that the molecular gas of NGC 1266 is energized by a $\approx 30 \text{ km s}^{-1}$ C-shock with a pre-shock density of $\approx 2 \times 10^4 \text{ cm}^{-3}$. A PDR produces the low-*J* CO emission, amounting to 0.14 of the observed CO luminosity. This may originate from the diffuse envelope surrounding the 60 pc core.

The discovery of shock-excited H₂O sets NGC 1266 and NGC 6240 apart from other galaxies studied in detail. Such strong emission has only been detected in extreme

environments, i.e., Arp 220 (Rangwala et al. 2011) and Mrk 231 (van der Werf et al. 2010). Unlike these other galaxies, NGC 1266 and 6240 lack emission from line transitions above 300 K (Figure 2, top-right), a signature of IR pumping, leaving shocks as the dominant mechanism. H_2O emission has proved to be a useful diagnostic to separate PDR and shocks, and of the galaxies compared here, NGC 1266 has the highest observed $L(\text{H}_2\text{O})/L(\text{TIR})$ ratio.

The CO line-to-continuum ratio (Meijerink et al. 2013) is a robust diagnostic of shock excitation. We propose that $[\text{C I}]$, which scales linearly with $L(\text{CO})$ over ≈ 2 dex, is also a powerful shock diagnostic. Another potential diagnostic is CO $J = (7-6)$; like $[\text{C I}]$, its ratio to total CO is nearly constant for all the galaxies in Figure 2. The utility of these lines will be explored further in our analysis of the entire BTP sample.

We conclude that the energetics of SF and AGN can both drive the observed shocks. A SF dominated energy source would explain the lack of high ionization potential IR emission lines usually detected in AGN, but not seen in NGC 1266 (i.e., $[\text{Ne v}]$, $[\text{O IV}]$; Smith et al. 2007).

Despite having an infrared luminosity more than 30 times less than that of a ULIRG, the compact molecular gas core in NGC 1266 has strikingly similar high gas surface density, including high-excitation, shocked gas and strong outflows. Thus it is possible for the bulk of a galaxy's gas reservoir to obtain the same extreme physical characteristics of a ULIRG, even within an otherwise quiescent stellar-dominated system.

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REFERENCES

- Aalto, S., Booth, R. S., Black, J. H., & Johansson, L. E. B. 1995, *A&A*, **300**, 369
- Alatalo, K., Blitz, L., Young, L. M., et al. 2011, *ApJ*, **735**, 88
- Allers, K. N., Jaffe, D. T., Lacy, J. H., Draine, B. T., & Richter, M. J. 2005, *ApJ*, **630**, 368
- Bothwell, M. S., Chapman, S. C., Tacconi, L., et al. 2010, *MNRAS*, **405**, 219
- Bournaud, F., Perret, V., Renaud, F., et al. 2013, *ApJ*, submitted (arXiv:1307.7136)
- Chiar, J. E., & Tielens, A. G. G. M. 2006, *ApJ*, **637**, 774
- Crocker, A., Krips, M., Bureau, M., et al. 2012, *MNRAS*, **421**, 1298
- Croxall, K. V., Smith, J. D., Wolfire, M. G., et al. 2012, *ApJ*, **747**, 81
- Dale, D. A., Smith, J. D. T., Schlawin, E. A., et al. 2009, *ApJ*, **693**, 1821
- Davis, T. A., Krajnović, D., McDermid, R. M., et al. 2012, *MNRAS*, **426**, 1574
- Farrah, D., Afonso, J., Efstathiou, A., et al. 2003, *MNRAS*, **343**, 585
- Flower, D. R., & Pineau Des Forêts, G. 2010, *MNRAS*, **406**, 1745
- Fukui, Y., & Kawamura, A. 2010, *ARA&A*, **48**, 547
- Habart, E., Dartois, E., Abergel, A., et al. 2010, *A&A*, **518**, L116
- Hollenbach, D., Kaufman, M. J., Neufeld, D., Wolfire, M., & Goicoechea, J. R. 2012, *ApJ*, **754**, 105
- Hopkins, P. F., Quataert, E., & Murray, N. 2011, *MNRAS*, **417**, 950
- Kamenetzky, J., Glenn, J., Rangwala, N., et al. 2012, *ApJ*, **753**, 70
- Kennicutt, R. C., Jr., Armus, L., Bendo, G., et al. 2003, *PASP*, **115**, 928
- Kennicutt, R. C., Calzetti, D., Aniano, G., et al. 2011, *PASP*, **123**, 1347
- Meijerink, R., Kristensen, L. E., Weiß, A., et al. 2013, *ApJL*, **762**, L16
- Meijerink, R., & Spaans, M. 2005, *A&A*, **436**, 397
- Meijerink, R., Spaans, M., & Israel, F. P. 2007, *A&A*, **461**, 793
- Pellegrini, E. W., Baldwin, J. A., Ferland, G. J., Shaw, G., & Heathcote, S. 2009, *ApJ*, **693**, 285
- Rangwala, N., Maloney, P. R., Glenn, J., et al. 2011, *ApJ*, **743**, 94
- Riffel, R., Rodríguez-Ardila, A., Aleman, I., et al. 2013, *MNRAS*, **430**, 2002
- Rigopoulou, D., Hurley, P. D., Swinyard, B. M., et al. 2013, *MNRAS*, **434**, 2051
- Smith, J. D. T., Draine, B. T., Dale, D. A., et al. 2007, *ApJ*, **656**, 770
- Tielens, A. G. G. M., & Hollenbach, D. 1985, *ApJ*, **291**, 747
- van der Werf, P. P., Isaak, K. G., Meijerink, R., et al. 2010, *A&A*, **518**, L42
- White, N. E., Gimmi, N. E., & Angelini, L. 1995, The WGACAT Version of the ROSAT PSPC Catalogue, Rev. 1 (1wga), <http://heawww.gsfc.nasa.gov/users/white/wgacat/wgacat.html> CDS
- Wolfire, M. G., Hollenbach, D., & McKee, C. F. 2010, *ApJ*, **716**, 1191
- Yang, C., Gao, Y., Omont, A., et al. 2013, *ApJL*, **771**, L24